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VALIDATION OF BOUNDARY-LAYER WINDS FROM WRF MESOSCALE FORECASTS WITH APPLICATIONS TO WIND ENERGY FORECASTING

Caroline Draxl,* Andrea N. Hahmann, Alfredo Peña, Jesper N. Nissen, and Gregor Giebel
Risø National Laboratory of Sustainable Energy
Technical University of Denmark, Roskilde, Denmark

Abstract

We evaluate forecasts made with the WRF ARW model run with seven different boundary layer (BL) parameterizations. The simulations are evaluated in terms of the best performance in wind energy forecasting, i.e. in forecasting winds at hub height as well as the correct shape of the wind shear. The model runs are short-term wind forecasts (0–30 hours) for October 2009 and are compared to measurements from the 116/160-meter meteorological mast/light tower at the Risø National Test Station for Large Wind Turbines at Høvsøre, Denmark. When evaluating wind profiles, we compute the α-parameter, a measure for stability derived from the power law. The results show that the YSU BL scheme does not exhibit the desired variation in the wind profiles from stable to unstable in the course of a day and tends to nearly always produce vertical wind shear typical of the neutral atmosphere. The wind profiles forecast with WRF using the BL schemes based on turbulence kinetic energy, however, compare better with the observations. All the evaluated schemes tend to underestimate the wind at hub height during the night and overestimate it during the day. The diurnal evolution and the expected transitions of wind speed, temperature and the α-parameter are well captured by all of the schemes, except for the YSU scheme.

1. Introduction

Especially in Denmark, with a wind power share in the electricity supply of more than 20%, wind forecasts are important for both wind farm operators and Transmission System Operators. Power fluctuations in a wind farm are mainly caused by wind fluctuations. At the Horns Rev 1 and 2 wind farms, the installation of 360MW within a fairly small area means that only minimal smoothing of output occurs in the event of high-frequency wind fluctuations. This arrangement can be challenging for grid operators. In Denmark, transmission system operators and wind farm operators bid the power on the energy market for the day ahead, and have the possibility to correct their forecast up to half an hour before delivery. Every deviation from the bid power results in a penalty cost. Consequently, bidders of wind power are interested in getting a reliable wind forecast. Improving wind forecasts makes therefore both economic and technical sense. The Danish National Laboratory for Sustainable Energy (Risø DTU) carries out research in close collaboration with the industry to improve wind forecasts for wind energy production and wind resource assessment.

Because the BL schemes play a significant role in the evolution of the low-level wind structure, we evaluate forecasts made with the NCAR Weather, Research & Forecasting (WRF) model run with seven different BL schemes. We evaluate the model results in terms of their accuracy in forecasting wind speed at various levels to select a satisfactory model setup. We compare the model output with measurements from a meteorological tower at Høvsøre in the west coast of Jutland, Denmark. In addition to the discussion of the results, we also want to emphasize some issues worth considering when it comes to selecting the best model configuration for wind energy forecasting.

2. Reference site: Høvsøre

We evaluate the model at the nearest grid point over land to our reference site Høvsøre. Høvsøre is the National Test Station for Large Wind Turbines, and is situated on the northwest coast of Denmark, close to the North Sea (see Fig. 1). The terrain around the site is relatively flat and homogeneous and at a distance of 1.7 km from the coast. The prevailing wind directions are west and northwest. A measurement tower has been observing winds at that site at a height of 10 to 116m for about 5 years. Data from a light tower nearby are available at 160m and complement the tower measurements. Recent studies used data from that site include [1], [2], and [3]. When winds are from north, the mast is unfortunately situated in the wake of wind turbines. During the evaluation period (October 2009), winds between 300

*Corresponding author: Caroline Draxl, Risø-DTU, Frederiksborgvej 399, P.O.Box 49, 4000 Roskilde, Email: cadr@risoe.dtu.dk

Figure 1: National Test Station for Large Wind Turbines, at Høvsøre, Denmark.

and 60 degrees occurred in approximately 30% of the time. The data used in our study are 10 min sustained wind speeds at 10, 40, 60, 80, 100, 116, 160 meters; temperature measurements at 2, 10, 20, 40, 60, 80, 100, 160 meters; and heat fluxes measured by sonic instruments. The friction velocity u_* and the Monin-Obukhov length L are computed with the heat fluxes.

3. Model setup

Risø maintains a real-time weather forecasting system for Denmark based on the WRF model. The setup is described in [4]. We use the same basic setup for the month of October 2009. The forecasts are 30 hours in length initialised at 12:00 UTC each day. The setup consists a main grid (with horizontal resolution of 18 km) and 2 nested domains (6 and 2 km grids), the innermost domain covering most of Denmark (Fig. 2). The model is initialized and forced at the boundaries by 1° NOAA Global Forecast System analysis and forecasts and the sea surface temperature fields from NCEP analysis at 0.5°. We use 2-way nesting and 37 vertical levels, with 8 levels within the lowest 500 m. The lowest levels which are important for wind energy applications are located at approximately 14, 52, 104 and 162 m. The model physics options include: Thompson graupel scheme, Kain-Fritsch cumulus parameterization, 6th order numerical diffusion, and positive definite advection of moisture and scalars. No data assimilation or grid nudging is used in the forecasts.

The model is run with seven different BL schemes, as indicated in Table 1: the Asymmetric Convective Model (ACM2) [5], the Medium Range Forecast Model (MRF) [6], Mellor-Yamada-Janjic (MYJ) [7], Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2) [8], Mellor-Yamada Nakanishi and Niino Level 3 (MYNN3) [9], Yonsei University Scheme (YSU) [10] and the Quasi-Normal Scale Elimination (QNSE) [11]. For the land surface

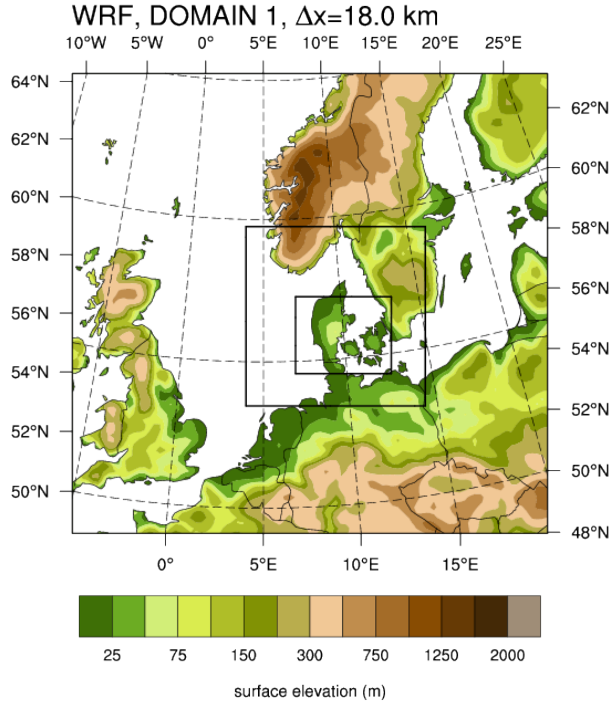

Figure 2: Domain configuration and terrain elevation of WRF model setup. The black squares indicate the boundaries of two nested domains.

model and the surface layer physics we choose the recommended options as in [12], also included in Table 1. All other parameterizations remain the same.

October 2009 was the period of choice because of the varied weather situations that occurred during this month. The synoptic situation in October 2009 in Denmark was characterised by a low pressure system over Scandinavia during the first few days, interrupted by a ridge on the 5th of October. From the 9th October, and for about 10 days onwards, anticyclonic conditions prevailed accompanied by stable conditions at night and unstable conditions during the day. After that, a low over western Europe with neutral and slightly unstable conditions determined the weather conditions over Scandinavia again, followed by a high pressure system and stable conditions during night times by the end of the month. In Denmark stable weather situations occur quite often. October 2009 constituted thus a month that can provide representative statistics of weather conditions.

4. Evaluation of seven BL schemes

Hahmann and Peña [4] point out that the friction velocity u_* is systematically over-predicted in Risø's real-time forecasts. This is partially due to surface roughness lengths that differ in the model and real world. Since the WRF land surface uses larger than observed values

Table 1: The seven BL schemes used in our comparison with their associated land surface models and surface layer physics, as recommended in [12]. The abbreviations in the first column are explained in section 3..

BL scheme	Land surface model	Surface layer
ACM2	Pleim-Xu	Pleim-Xu
MRF	Unified Noah LSM	Monin-Obukhov
MYJ	Unified Noah LSM	Eta similarity
MYNN2	Unified Noah LSM	MYNN
MYNN3	Unified Noah LSM	MYNN
YSU	Unified Noah LSM	Monin-Obukhov
QNSE	Unified Noah LSM	QNSE

of surface roughness, the model physics tends to compensate their effect to get the wind forecasts right above the BL. This is done by artificially enhancing the value of u_*. The paper also shows that the heat fluxes forecast by the model are about right. However, the sign of the surface heat flux does not seem to properly influence the shape of the wind profile. Their results show, that in the real-time forecasts, which use the YSU BL scheme, the forecast wind profiles are those produced by neutral stratification most of the time. The main reason for this behaviour is that the Monin-Obukhov length, L, which depends on u_*^3, is overestimated and thus underestimates the term z/L. z/L is then used to compute the stability correction to determines the wind profile ([13]). An underestimated z/L leads to near neutral conditions. Storm and Basu [14] also found that the YSU scheme tends to "neutralize" the wind profiles. They explain its failure by excessive mixing of the stable BL, which destroys near-surface shear.

A parameter often used to diagnose the shape of the wind shear is α, which is given by defined as

$$\alpha = \frac{ln[u(z_2)/u(z_1)]}{ln(z_2/z_1)} \quad (1)$$

where $u(z_1)$ and $u(z_2)$ are the wind speed at a levels z_1 and z_2 [15]. In our calculations, z_1 and z_2 are 10 and 60 m in the observations. In the model we use the first two model levels. A value of $\alpha = 1/7$ (0.143) is regarded to represent neutral conditions, smaller (larger) values represent unstable (stable) atmospheric BL conditions.

4.1. How is the stability parameter captured by the seven BL schemes?

The weather situation during October 2009 can be analysed by looking at stability conditions in terms of α. In Fig. 3 we show α for each forecast time and day of the month. The last panel shows the observed values. Times with $\alpha > 1/7$ dominate, especially during the night, whereas $\alpha < 1/7$ during daytime and situations with unstable conditions (e.g. weather dominated by a low pressure system). The pattern of variation in the observations is fairly well captured by all of the BL schemes, except for the YSU scheme. The latter shows neutral conditions (light green color) for most of the month at all times of the day. The block of stable nighttime conditions from 9-19 October was captured best by the turbulence kinetic energy (TKE) based schemes, MYNN2, MYNN3, and QNSE. However, MYNN2 and MYNN3 depicted the period from about 19 to 26 October too stable compared to the observations. They did capture the stable conditions during the last day of the month, though, which none of the other schemes did with that accuracy. The very low α values from the observations during the daytime were not captured in that magnitude by any of the schemes.

4.2. How do the seven BL schemes capture the evolution of the diurnal cycle?

As mentioned in the Introduction, models tend to be challenged during transition times, namely during sunrise and sunset. With Fig. 4 we want to estimate, how the diurnal cycle and transitions are represented in the model forecasts. The figure shows averages of various parameters for the month of October 2009 as a function of time of the day. The valid time (in UTC) is one hour behind local time in Denmark. In general, the forecast wind speeds of the seven BL schemes follow quite closely (within $\sim$ 1m s^{-1}) those of the observations (green line). Most of the schemes tend to underestimate the wind speed at 10 m especially during nighttime, except for the YSU and the MYJ scheme, which show the highest wind speeds of all schemes. Higher up at 60 m, the BL schemes tend to overestimate the wind during daytime and underestimate it during nighttime. That same pattern continues at 160 m. The transition times are nevertheless well captured.

The temperature at 2 m is overestimated by up to 2°C by all the schemes, with the YSU scheme being the warmest. In contrast, all schemes underestimate (by 0–2°C) the temperature at hub height (55 m), with QNSE and MYJ being the coldest.

As pointed out in section 4. with regard to real-time runs with the YSU schemes, although the other BL schemes overestimate the friction velocity u_*, the YSU scheme however overestimates it the most. The transitions are captured satisfactorily. The heat flux is very well captured in magnitude and by all the schemes. Its maximum is 1–2 hours later in the model runs compared to observations.

As indicated in the previous figure, the diurnal cycle with its transitions of the stability parameter α is in good agreement with the observations by most of the schemes. However, the YSU scheme shows no variation in time, which confirms the findings by Hahmann

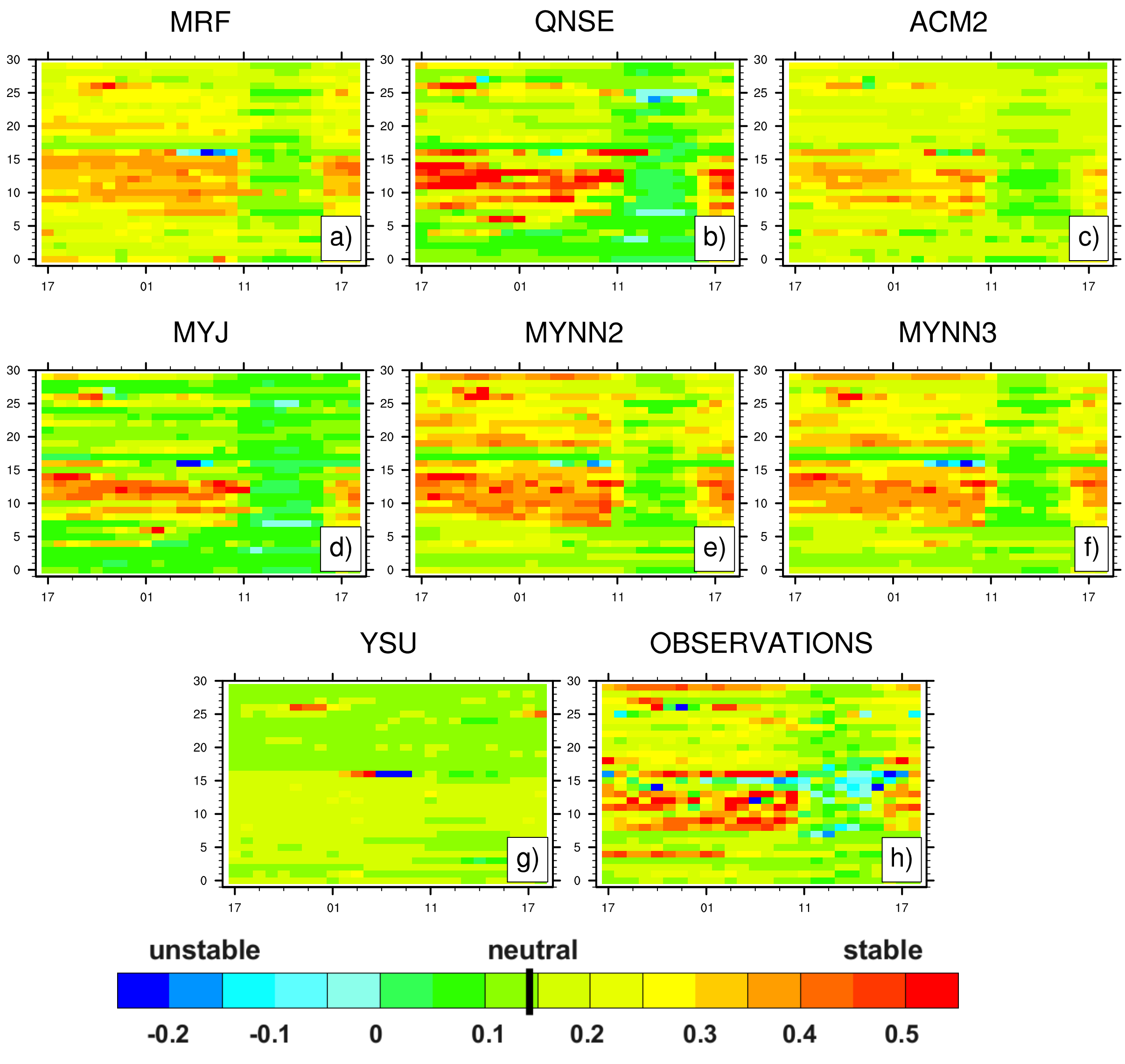

Figure 3: Stability parameter, α, as a function of time of the day (UTC, x-axis) and day of the month (y-axis). The title above each subplot indicates the BL scheme used with each model run. Panel h) represents the observations.

and Peña [4], that that YSU scheme forecasts neutral conditions most of the time.

5. Discussion

The results presented give an overview on how the forecasts performed with our WRF model setup perform with regard to wind energy forecasting compared to a site at the northwest coast of Denmark, Høvsøre. This site was chosen because of its data availability from 10 to 160 m, which allows us to evaluate wind profiles. Another reason for our interest in that site is its vicinity to the Horns Rev 1 wind farm, for whose operators Risø provides wind forecasts.

There are many ways to evaluate numerical weather forecasts. In this section we discuss some ideas about which settings could change our results.

The statistics depend on the grid point chosen and the site of comparison. Høvsøre is near the coast and located in flat and homogeneous terrain, and although we choose the nearest grid point over land to be compared with the measurements, there might still be some land/sea interaction mechanism that influences this grid point. Likely there are influences of sea/land breezes, internal BL or low level jets. Further research should include comparing the measurements to other grid points more inland and over the sea as well as looking at spatial averages.

The results of such a study also depend on the model setup, i.e. selection of boundary conditions and/or domain sizes. One could argue that the the model is more skillful when more levels are used. The height of the first model level is apparently important [16], because it determines the minimum height of the surface layer and thus influences the surface fluxes. The variability of surface fluxes is correlated to the roughness length z_0, the atmospheric stability and advection [17]. A more accurate representation of z_0 could therefore result in better forecasts [18].

We used the Noah Land surface model [19] for six of the seven runs. The choice of the land surface model and treatment of soil moisture could influence the results. Recent studies [20] seem to indicate that soil moisture is one of the most sensitive parameters in simulating wind speeds.

Our evaluation is driven by the setup of our real-time forecast system, that was only altered by using different BL schemes. A real-time forecast system is constrained to be computationally inexpensive (short computing time, not too many vertical levels, adequate horizontal resolution), which justifies our setup options.

6. Conclusion and Outlook

We evaluate the WRF ARW model [12], run with seven different BL schemes for one month, as to which one shows the best performance in terms of wind energy forecasting. We analyse how well the various schemes are able to accurately forecast the wind profiles as well as the diurnal evolution of various BL properties. It has been shown, that the runs that used the YSU BL scheme exhibit very little variation in the wind profiles from stable to unstable conditions. Thus, there is a tendency within the YSU BL scheme to always produce neutral wind profiles. The TKE based schemes (MYNN2, MYNN3, QNSE) seem to do the best job in reproducing the observed characteristics of the wind profiles. Since the forecasting of wind profiles is important in wind energy, these BL schemes should be preferred for forecasting wind conditions in Denmark.

When analyzing the diurnal evolution of BL parameters, we conclude that all the evaluated schemes tend to underestimate the wind at hub height during the night and overestimate it during the day. The characteristics of the diurnal cycle and their transitions are in general well captured by all the model runs.

Our results are valid for October 2009. Long term studies with the same model setup for the YSU BL scheme showed [4], that the error of the model depends on seasonality and stability, which means that the results could look slightly different when evaluated in different months. Ongoing work will therefore include stability analyses as well as performance of the different schemes during LLJ events.

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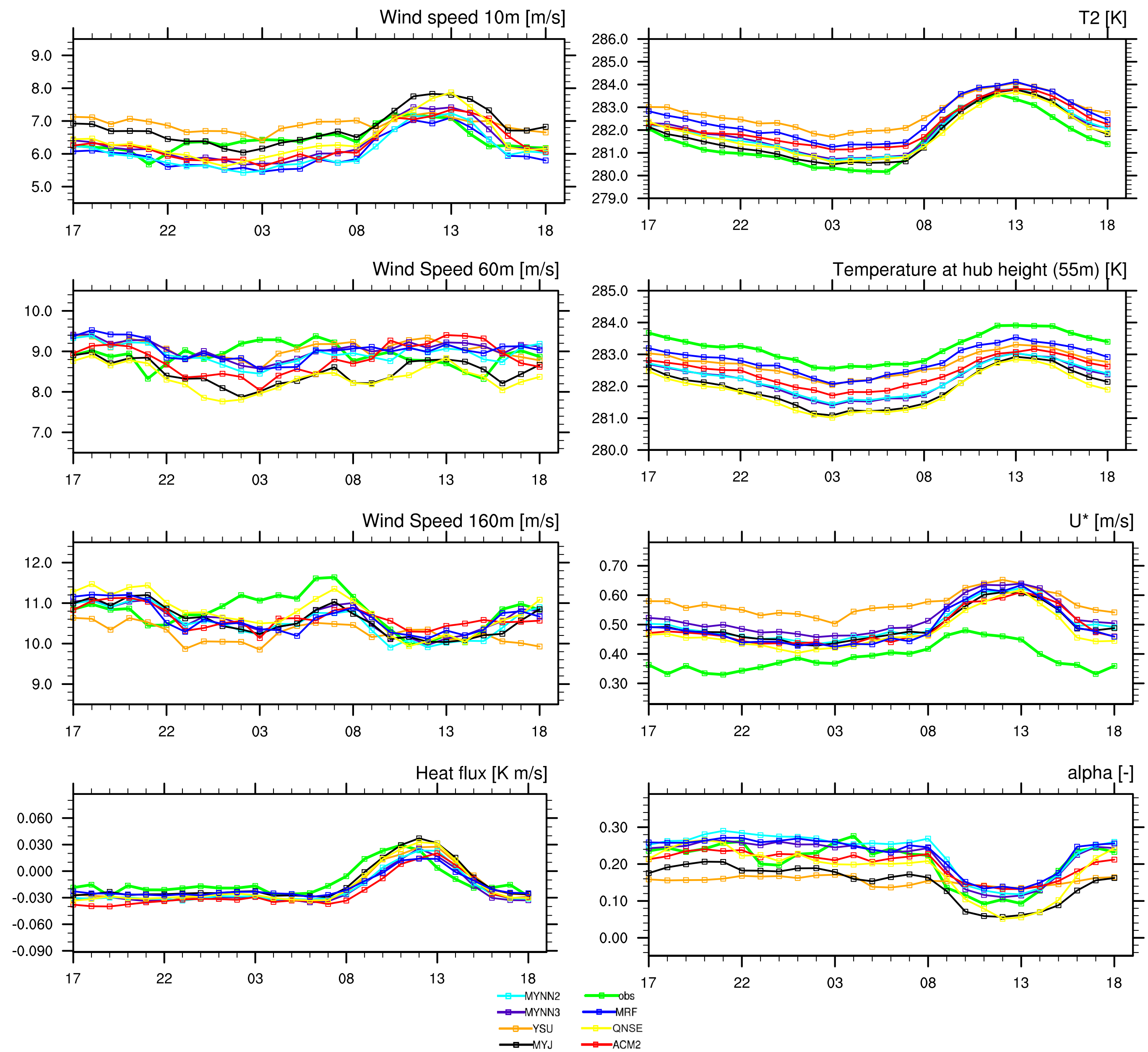

Figure 4: Mean diurnal evolution for October 2009 of various variables extracted from the grid point at Høvsøre for each of the BL schemes. The panels from top to bottom and from left to right are: wind speed 10m, 60m, 160m, heat flux, Temperature at 2m, Temperature at hub height (55m), friction velocity u_* and α as a function of time of the day (UTC hours).

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